Fluid-Structure-Control-Interaction for Smart Rotors

Implementation in OpenFOAM

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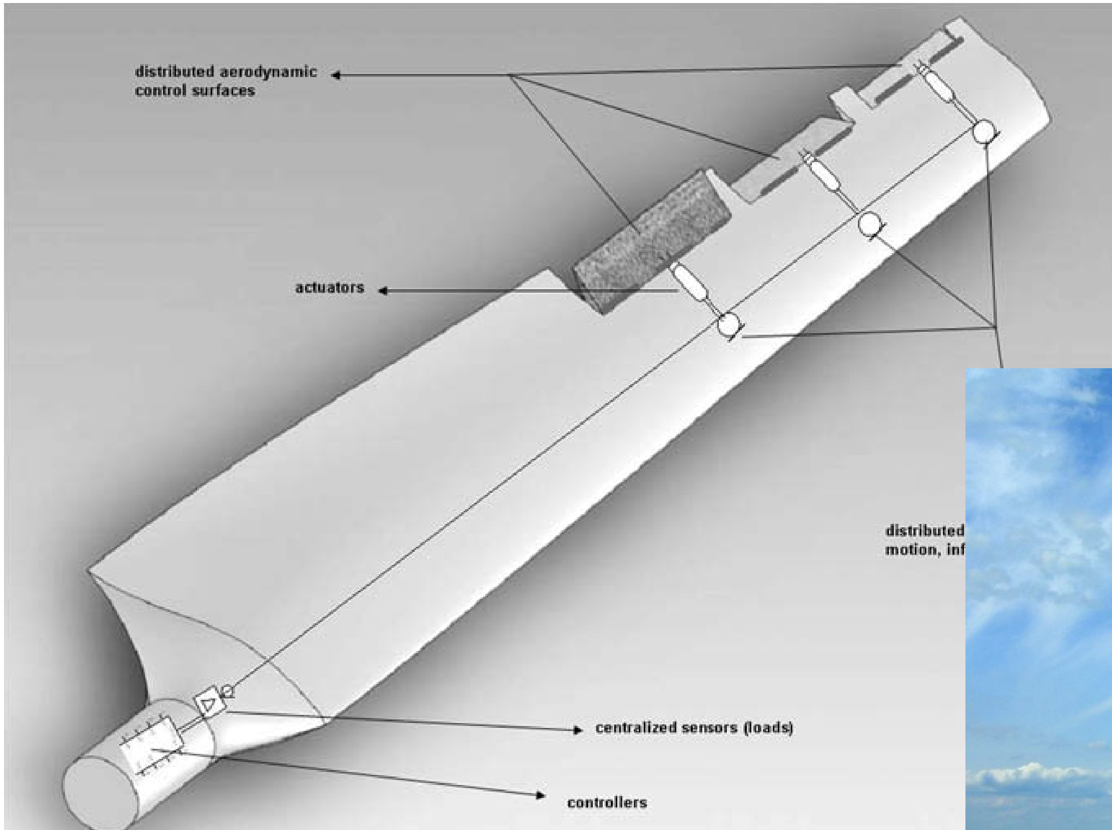
Smart Rotor



- Decrease CoE
- Reduce (fatigue) loading
- Increase diameter

Content

- Unsteady Aerodynamics on Moving Meshes
  - Order behavior
  - RBF mesh deformation
  - Flap motion (local deformation)
- Fluid-structure-interaction
  - Coupling scheme
  - Order behavior
- Gusts
  - Mesh Velocity Technique
- Fluid-Structure-Control-Interaction
  - Controlled response of an airfoil to gusts

Unsteady Aerodynamics

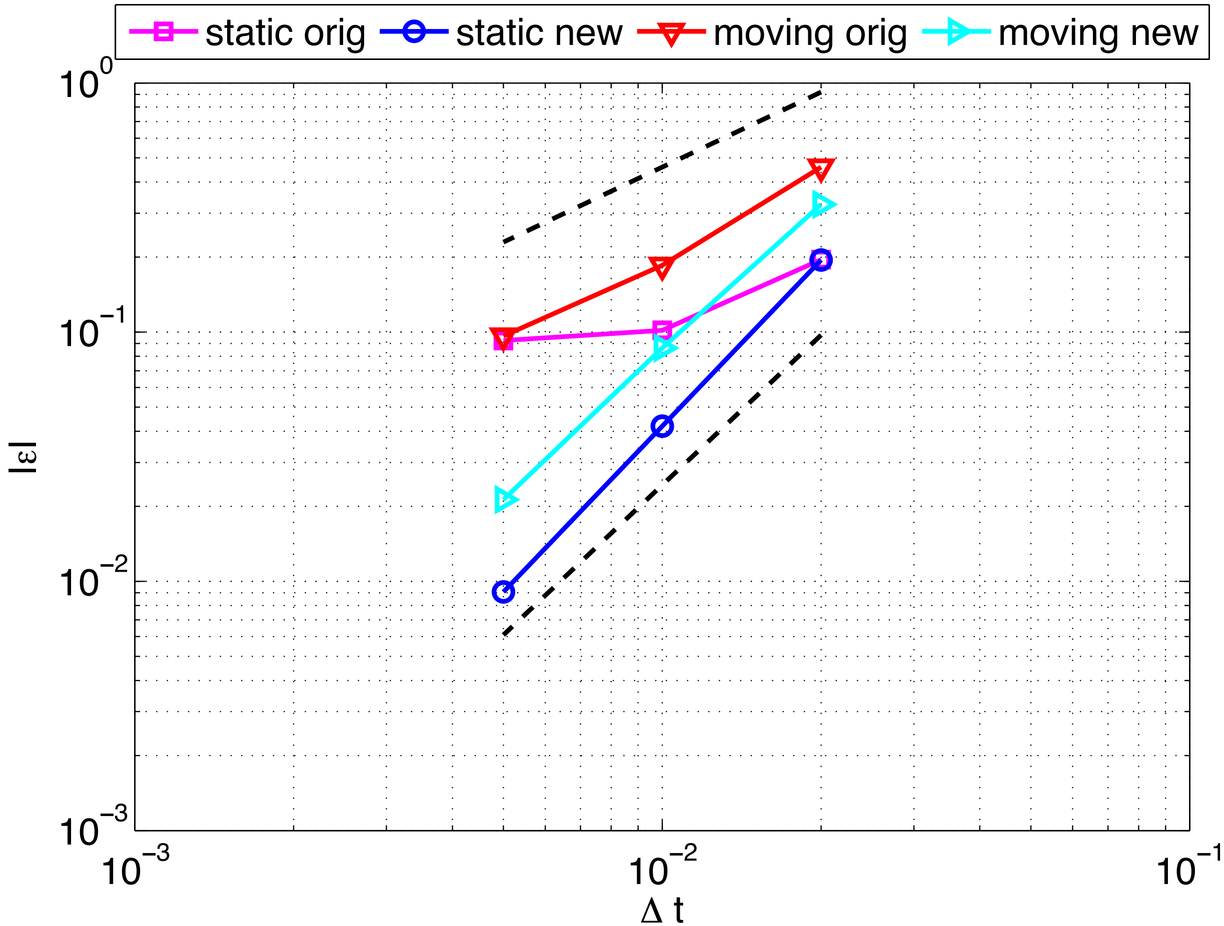
Consistent Time Order Behavior

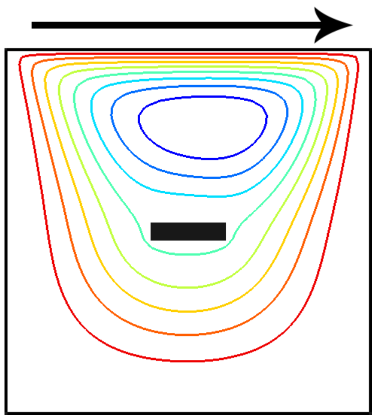
- Correct Rhie-Chow Interpolation in PISO algorithm[1]
  - Inconsistent interpolation to faces
  - Key aspect: interpolate AU to faces instead of 1/AU
- For moving meshes additional ddtPhiCorrection[1] need to be adjusted
  - Incorporate cell volume changes and surface normal changes
- One additional change is needed for boundary condition on moving wall
  - 2nd order derivation of velocity at boundary

[1]Tukovic, Z and Jasak, H., 2012. "A moving mesh finite volume interface tracking method for surface tension dominated interfacial fluid flow". Computer & Fluids, **55**, p. 70-84.

Unsteady Aerodynamics

2^{nd} order temporal accuracy on moving meshes



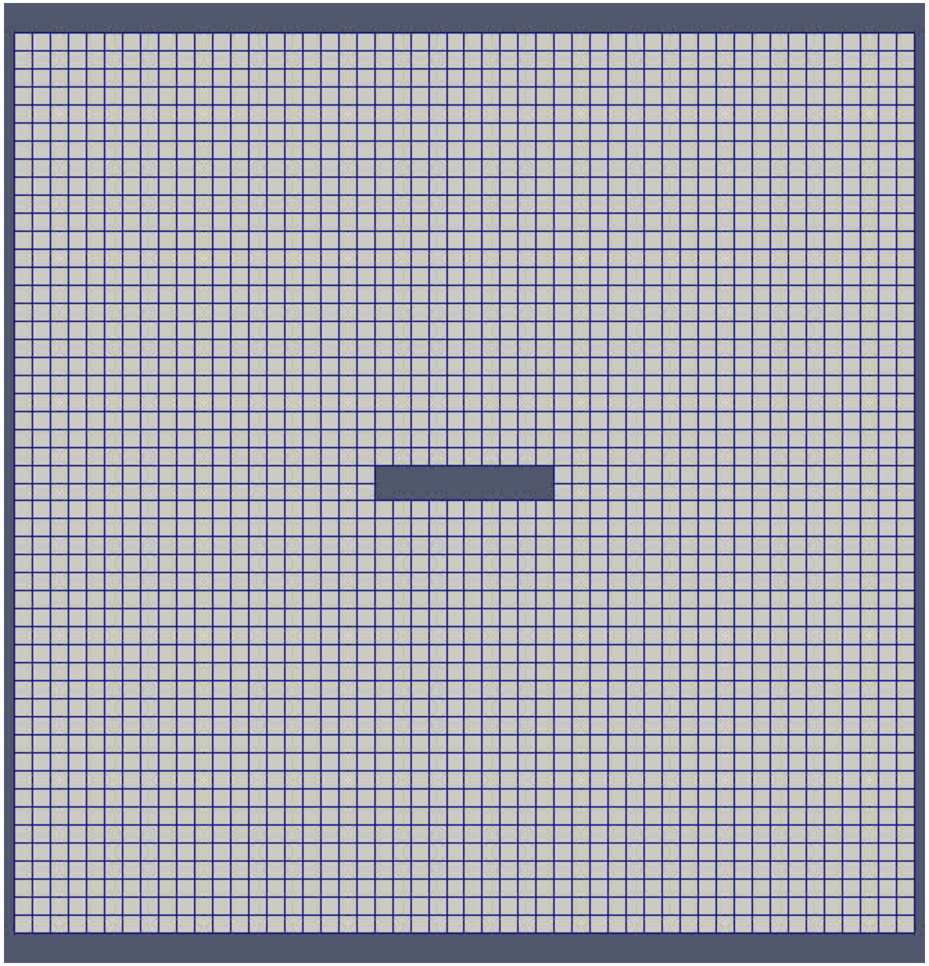


Unsteady Aerodynamics

RBF mesh deformation

Interpolation of body motion to internal mesh

- Point to point interpolation
- Displacement of points on boundaries (moving+static) interpolated to internal points
- Independent of mesh connectivity



Unsteady Aerodynamics

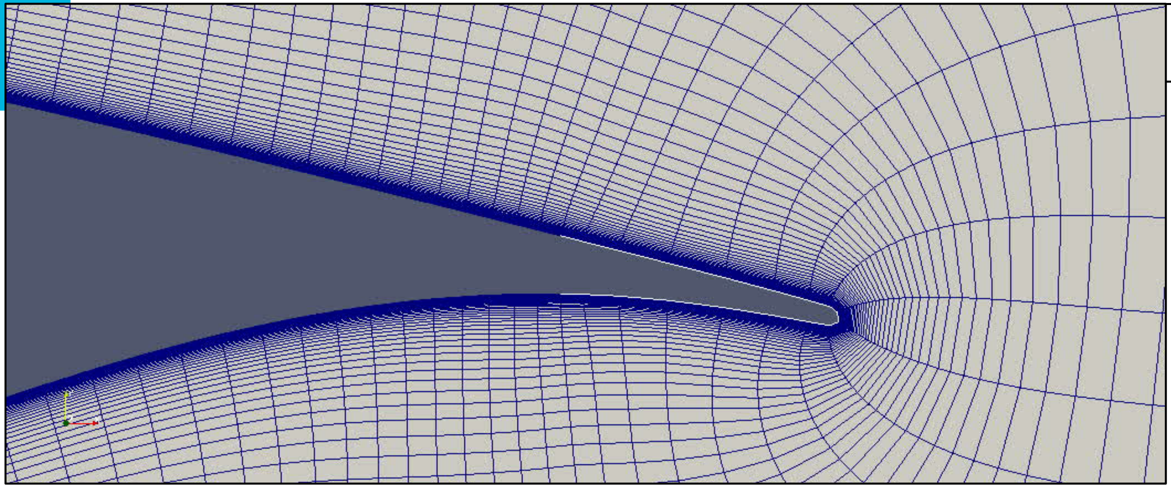
Reformulation of RBF mesh deformation

- Inefficient (slow and serial) implementation in OpenFOAM
- Reformulation and new implementation of RBF mesh deformation

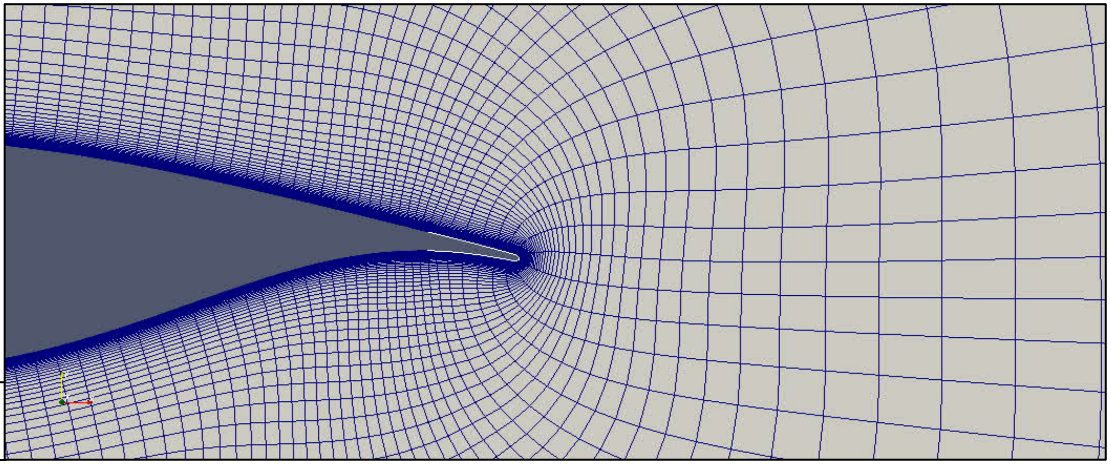
$$
\begin{aligned}
\begin{bmatrix} \Delta\mathbf{x}_c \\ \mathbf{0} \end{bmatrix} &= \begin{bmatrix} \Delta\mathbf{x}_m \\ \Delta\mathbf{x}_s \\ \mathbf{0} \end{bmatrix} = \mathbf{d}_c = A\beta \rightarrow \beta = A^{-1}\mathbf{d}_c \\
\Delta\mathbf{x}_i &= B\beta = BA^{-1}\mathbf{d}_c = H \begin{bmatrix} \Delta\mathbf{x}_m \\ \Delta\mathbf{x}_s = \mathbf{0} \\ \mathbf{0} \end{bmatrix} \\
\Delta\mathbf{x}_i &= H \begin{bmatrix} \Delta\mathbf{x}_m \\ \Delta\mathbf{x}_s = \mathbf{0} \\ \mathbf{0} \end{bmatrix} = H_m \Delta\mathbf{x}_m \\
H_m &= [N_i \times N_m]
\end{aligned}
$$

Unsteady Aerodynamics

Flap deformation



Hinged flap



Deforming flap

Fluid-Structure-Interaction

Coupling schemes

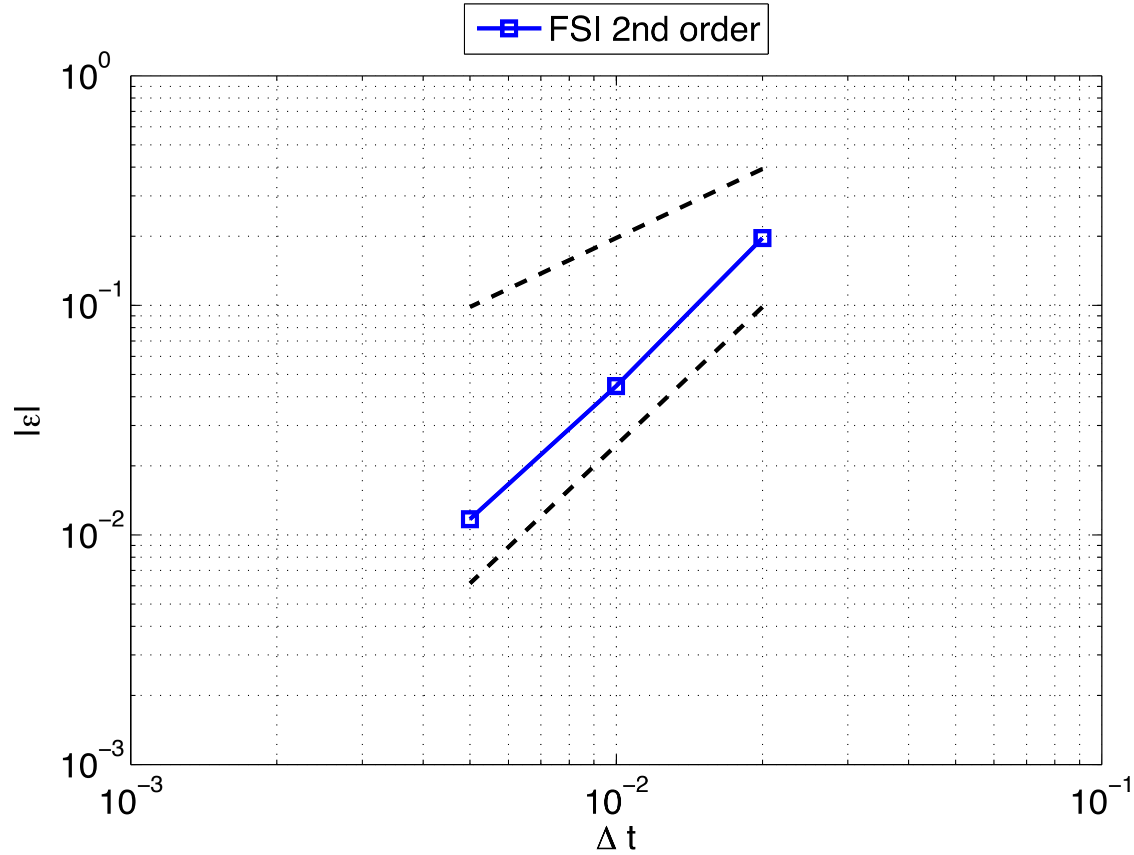
- Aitken's under-Relaxation

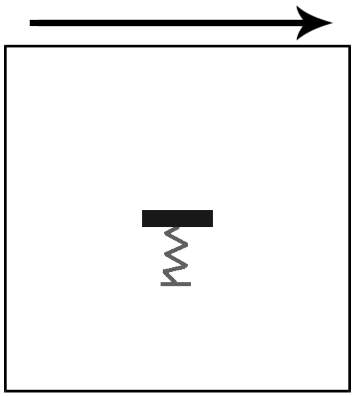
$$
\begin{aligned}
\tilde{\mathbf{p}}^{k+1} &= F \circ S\left(\mathbf{p}^{k}\right) \\
\mathbf{r}^{k} &= \tilde{\mathbf{p}}^{k+1} - \mathbf{p}^{k} \\
\mathbf{p}^{k+1} &= \mathbf{p}^{k} + \omega^{k}\left(\mathbf{r}^{k}\right) \\
\omega^{k} &= -\omega^{k-1} \frac{\left\langle \left(\mathbf{r}^{k-1}\right), \left(\mathbf{r}^{k} - \mathbf{r}^{k-1}\right) \right\rangle}{\left\langle \left(\mathbf{r}^{k} - \mathbf{r}^{k-1}\right), \left(\mathbf{r}^{k} - \mathbf{r}^{k-1}\right) \right\rangle}
\end{aligned}
$$

- High density ratio results in relative weak interaction
  - Low number of sub-interactions (~2)
  - No need for more efficient algorithm

Fluid-Structure-Interaction

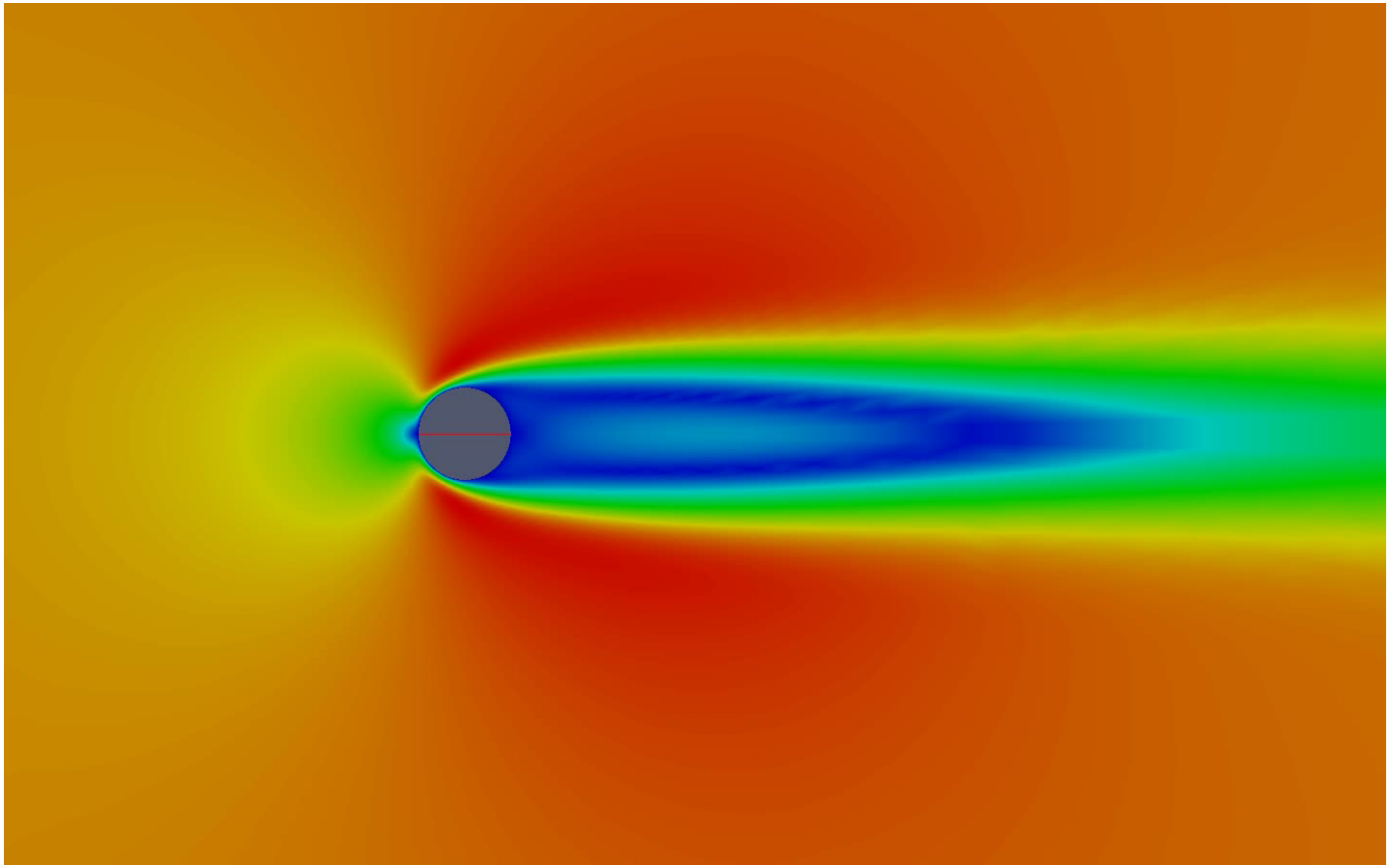
Order behavior





Fluid-Structure-Interaction

Cylinder responding to gust



Gust Inflow Conditions

Mesh velocity technique

- Numerical Technique
  - Use **mesh velocities** for gust velocities[2]
  - No actual mesh deformation
  - Artificial volume change to satisfy Discrete Geometric Conservation Law (DGCL)

- Any gust shape in space and time possible
  - Including non-physical gusts
  - No influence from fluid on gusts -> **one-way coupling**
  - **No diffusion**

[2]Singh, R. and Baeder, J.D., 1997. "Direct Calculation of Three-Dimensional Indicial Lift Response Using Computational Fluid Dynamics". Journal of Aircraft, **34**, p. 465-471.

Gust Inflow Conditions

Mesh velocity technique

Adjusted mesh velocity:

$$V = \mathbf{u} - \mathbf{u}_m + \mathbf{u}_g = \begin{matrix} u - u_m + u_g \\ v - v_m + v_g \\ w - w_m + w_g \end{matrix}$$

$$\tilde{\mathbf{u}}_m = \begin{matrix} \tilde{u}_m \\ \tilde{v}_m \\ \tilde{w}_m \end{matrix} = \begin{matrix} u_m - u_g \\ v_m - v_g \\ w_m - w_g \end{matrix}$$

OpenFOAM:

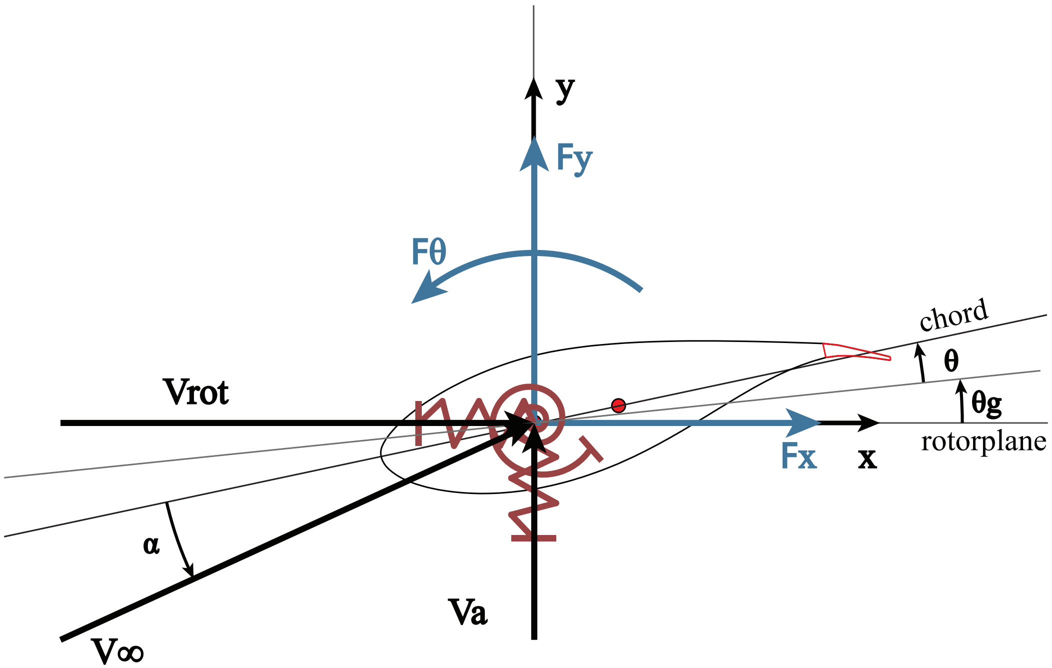
$$\text{makeRelative: } \phi_{rel} = \phi_{abs} - \tilde{\phi}_m = \phi - \tilde{\mathbf{u}}_m \cdot \mathbf{S}_f$$

$$\text{makeAbsolute: } \phi_{abs} = \phi_{rel} + \tilde{\phi}_m = \phi + \tilde{\mathbf{u}}_m \cdot \mathbf{S}_f$$

Aero-elastic Gust Response

Problem setup

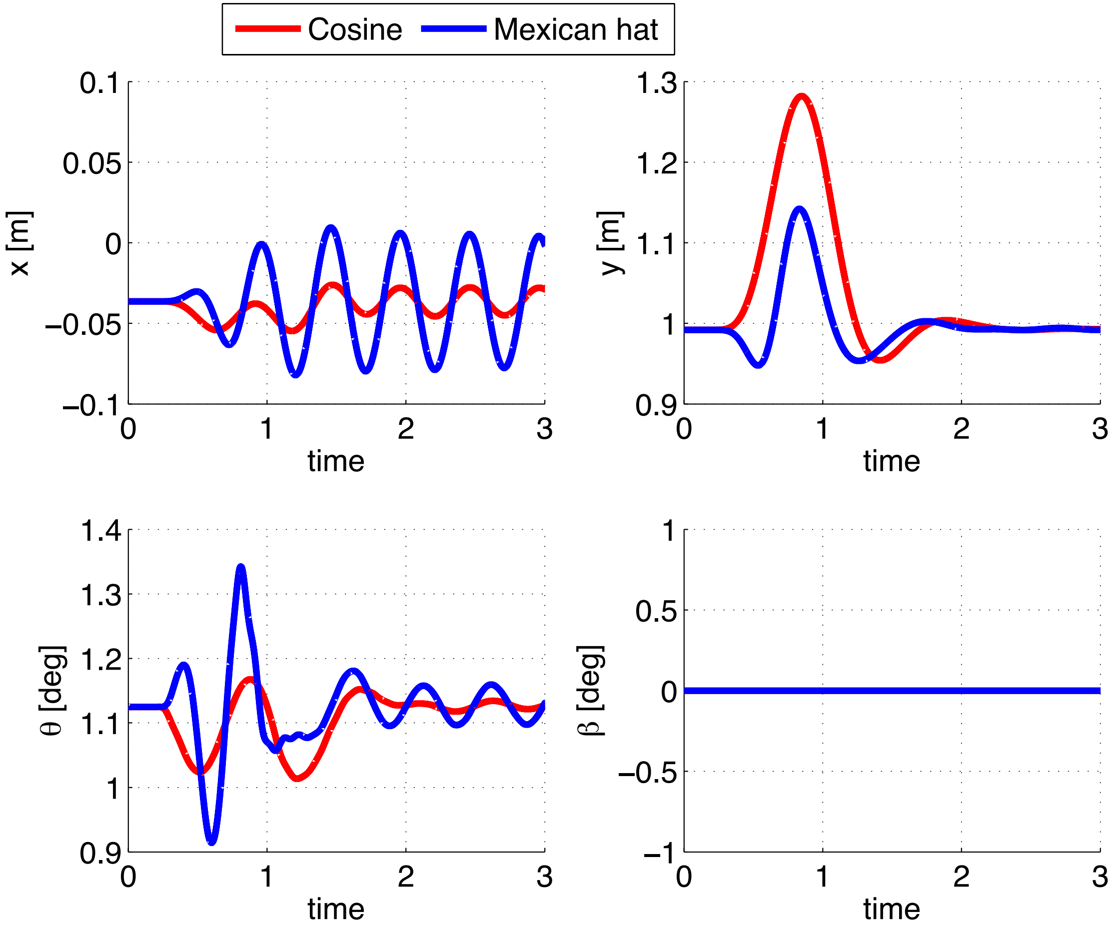
- 3 DoF rigid body
- Re = 4 million
- k-ω SST turbulence model
- Deforming trailing edge flap 10% of chord
- PID controller on vertical velocity



Aero-elastic Gust Response

Airfoil response to Cosine and Mexican-hat gusts

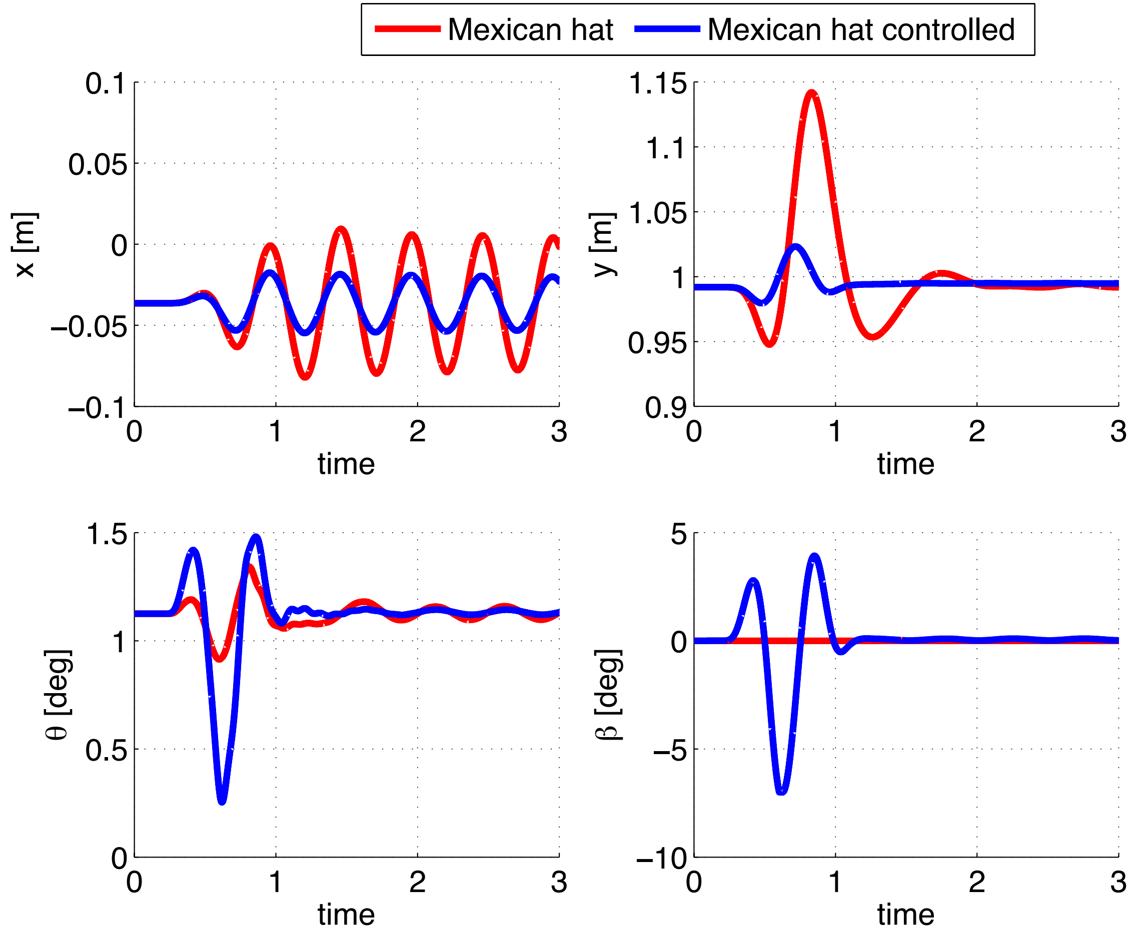
- x, y and θ displacement
- Large response in y for cosine gust
- Mexican-hat causes low damped response in x and θ



Aero-servo-elastic Gust Response

Response to Mexican-hat gust with controlled flap

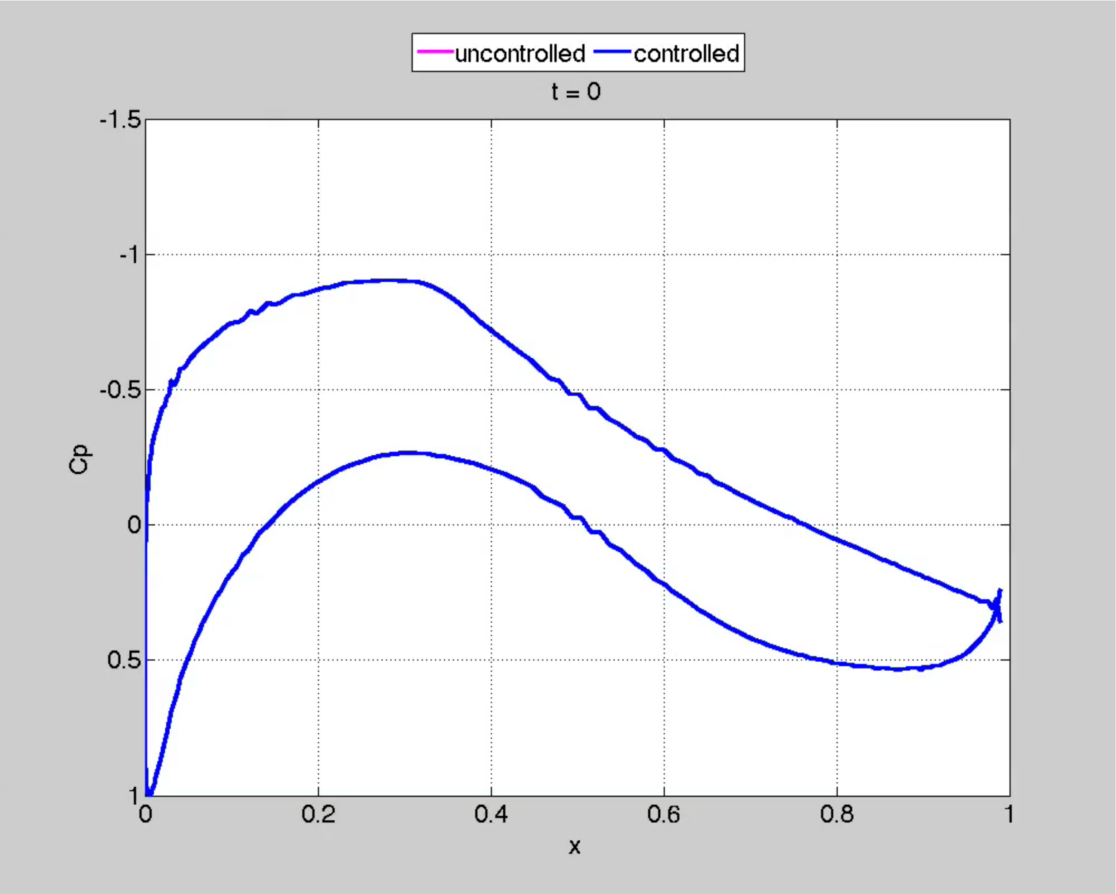
- x, y and θ displacement
- β (flap angle)
- 80 % reduction in y displacement
- Strong increase in pitch angle
- Similar results found in literature



Aeroelastic Gust Response

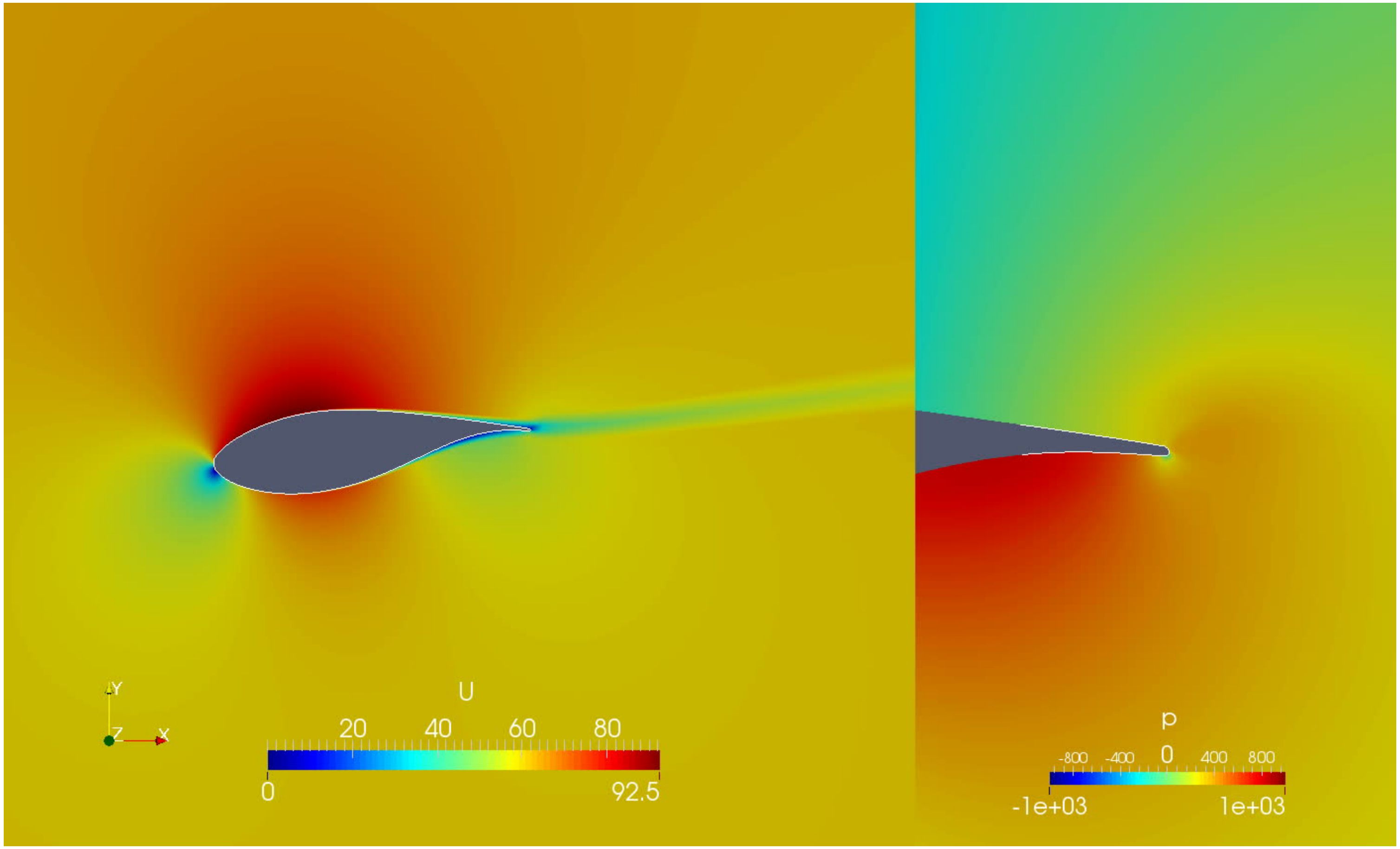
Pressure in time with and without flap control

- Reduced pressure differences in flap region reduces vertical force



Aero-servo-elastic Gust Response

Velocity and pressure results for airfoil response



Conclusions & Discussions

- Full 2D aero-servo-elastic time order consistent URANS model completed
  - RBF mesh deformation
  - FSI with Aitken's under relaxation
  - Gusts with mesh velocity technique
  - Parallelized FSCI solver with gusts
  - 2^{nd} order in time
- First results on aero-servo-elastic responses show similar behavior as reported in literature
  - Flap control can reduce deflections significantly
  - Flap control increases pitching angle significantly

Outlook

- Detailed comparison with engineering models
  - Different gust shapes: cosine, Mexican hat, turbulent inflow
  - Different gust parameters: amplitude, frequency
- Flap model
  - Maximum hinge moments
  - Maximum rotational speed
  - Controller delay
- 3D unsteady (FSI) blade simulations

Thank you for your attention

Questions?

Unsteady Aerodynamics

Order behavior

- Face flux
  - *Original:* phi = fvc::interpolate(HU/AU) & mesh.Sf()
  - *Correct:* phi = (fvc::interpolate(HU)/fvc::interpolate(AU)) & mesh.Sf()

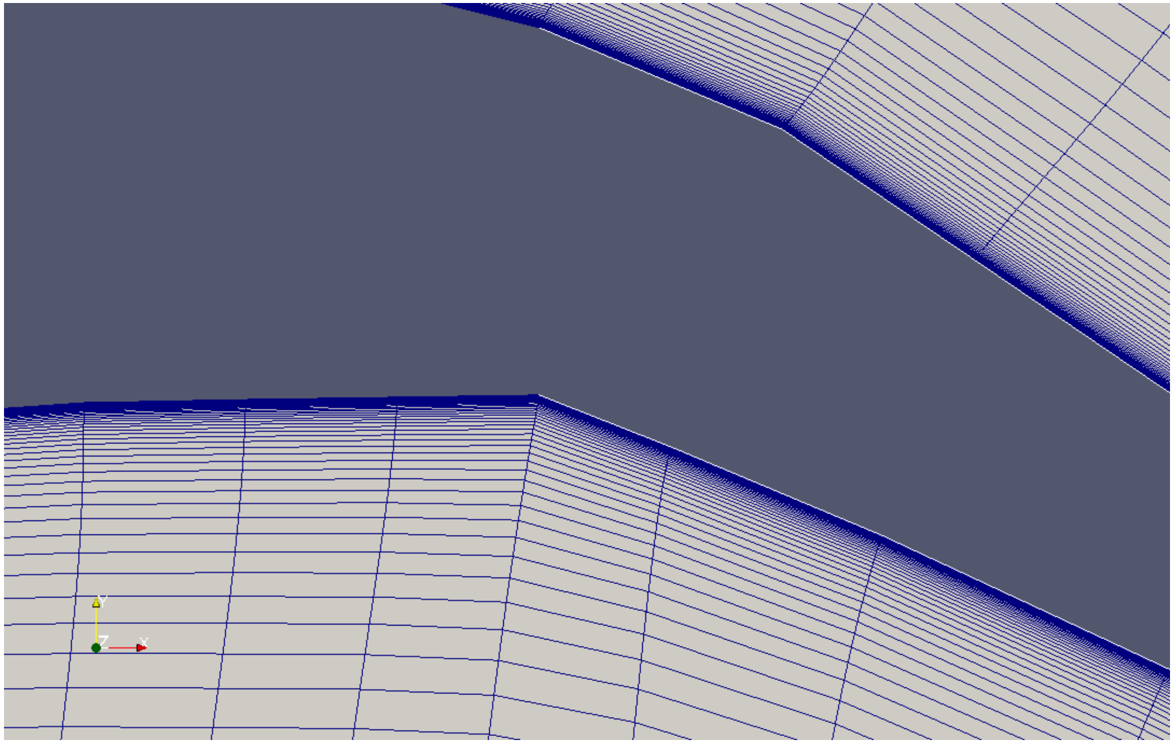
- ddtPhiCorr
  - *Original:* fvc::interpolate(1.0/AU)
  - *Correct:* 1.0/fvc::interpolate(AU)

- Laplacian
  - *Original:* fvm::laplacian(1.0/AU, p)
  - *Correct:* fvm::laplacian(1.0/fvc::interpolate(AU),p)

- Moving wall velocity boundary condition

Unsteady Aerodynamics

Deforming Boundary Layer Mesh



Unsteady Aerodynamics

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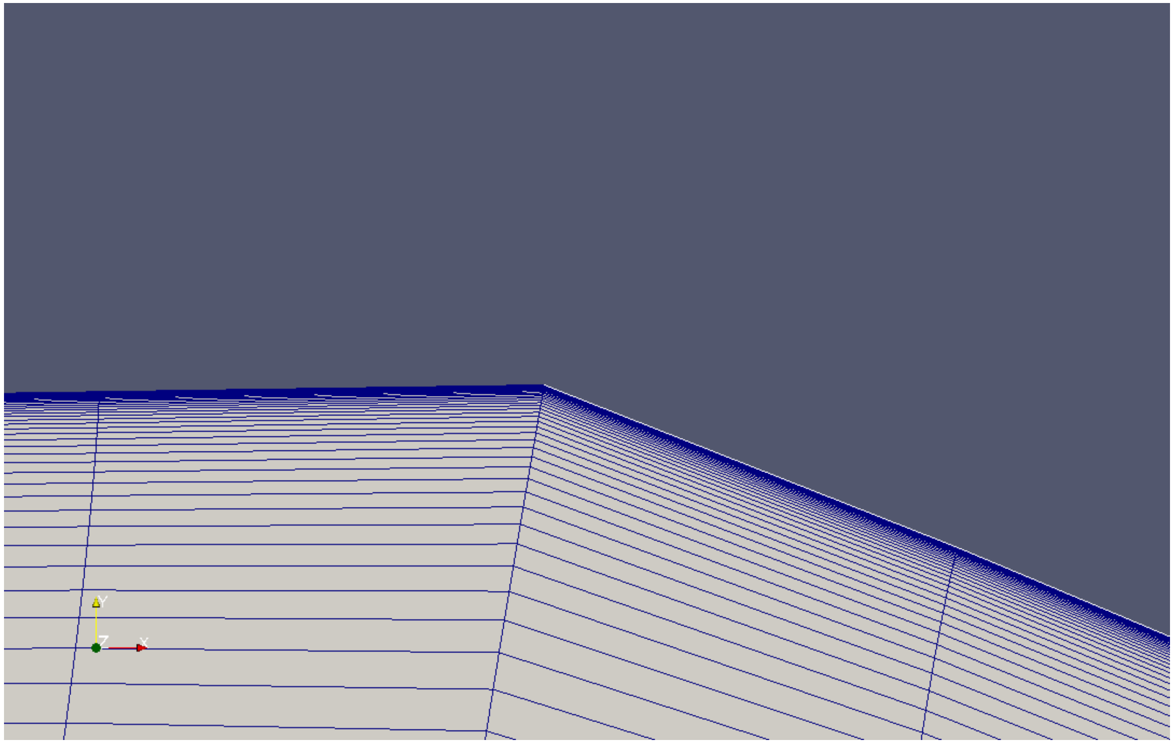
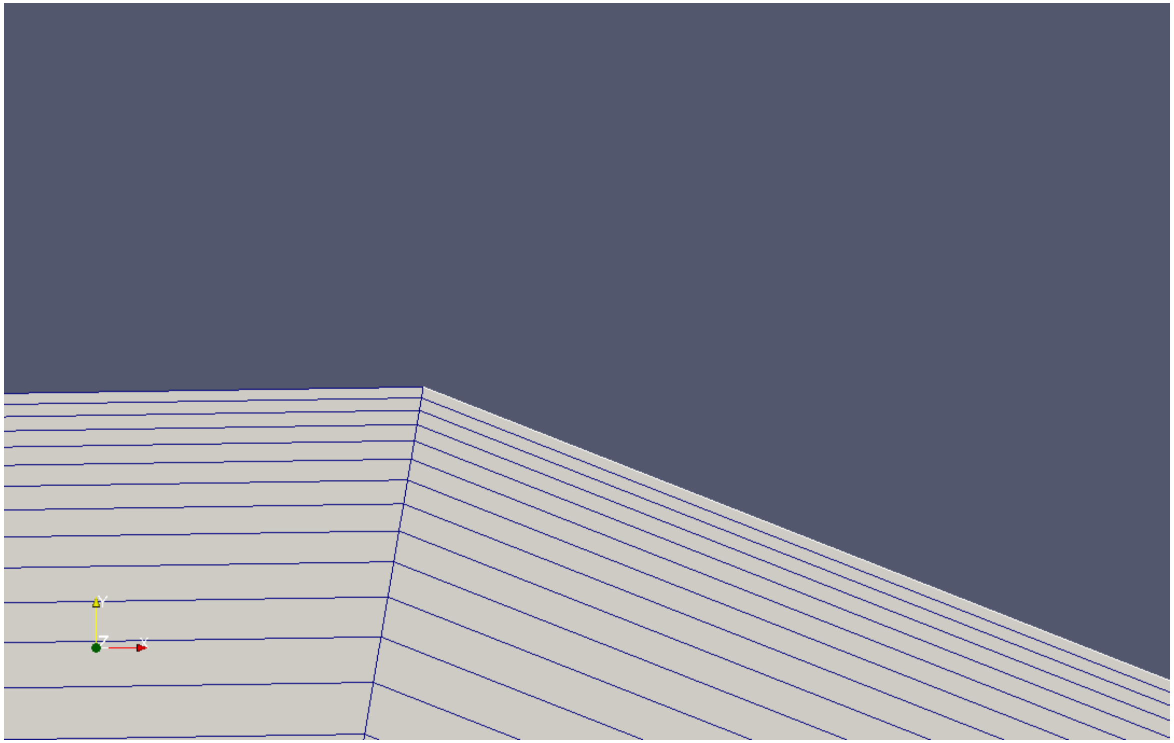


Unsteady Aerodynamics

Deforming Boundary Layer Mesh



Mesh Velocity Technique

DGCL

- DGCL -> Artificial volume changes

$$\frac{\partial}{\partial t}\int_{Vc} dVc = \sum_f \left(\frac{d\vec{x}}{dt}\bullet\vec{n}S\right)_f = \sum_f \left(\vec{u}_g\bullet\vec{n}S\right)_f$$